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A Goal-Seeking Strategy for Constructing Systems From Alternative Components

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May 2000

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Introduction

Designing large-scale systems often involves making selections from multitudes of alternative components, subsystems, and configurations. Each potential selection must be weighed against several design constraints, goals, and objectives. Many selections involve trading a gain in one system parameter against a loss in another. For example, in one design study there were over 800 modifications proposed for the Space Shuttle fleet [NASA, (22)]. Each of the proposed modifications affects system objectives for reducing weight, improving safety, increasing reliability, reducing operating costs, etc. A selection that improves safety may increase weight. A selection that increases reliability may increase operating costs. In addition, each modification consumes limited system resources such as power or budget.

In the Shuttle illustration, each alternative modification interacts across several system parameters. These parameters may be described by discontinuous functions, or not be tractable mathematically and may require simulations or look-up tables. To date, the only proven optimization method for this type of problem is an exhaustive search of all feasible combinations [Bascaran, et al., (2)]. For the Shuttle, no alternative or set of alternatives is obviously dominant or infeasible and few of the modifications are mutually exclusive. As such, each combination of modifications must be considered as a separate competing system. This results in over 2^{800} (10^{240}) component combinations to be evaluated. If one million combinations were evaluated each second, it would take 10^{227} years to perform this exhaustive search.

Selecting components against multiple criteria is common in engineering design. However, most system optimization theory focuses on varying design and performance parameters of predefined systems with fixed configurations. Parameters are varied either to minimize deviation from some ideal, or to maximize an objective function. Comparatively little work concerns defining initial system configurations or finding alternative configurations that offer improved performance.

The methodology, described in this paper, is designed to construct a feasible system by selecting components from large inventories of component types. It then modifies a feasible system (again by adding or removing components) to meet successive performance goals. When all goals are met, it modifies a system to enhance system performance as measured by an objective function. It is designed to do this in far fewer iterations than exhaustive search would require.

Background Concepts

To understand the methodology described in this paper, it is necessary to have a common understanding of certain definitions and for using "distance" to compare competing systems. For the purposes of this paper, a component is a nondivisible element that may be added to or removed from a system. A component has quantifiable and fixed properties. A system is a fixed set of components having well-defined boundaries and measurable effects on its environment. Parameters are single-term variables used to measure a single system or component effect (e.g. weight, length, cost). Any mathematical combination of parameters required to define some

system aspect defines a new parameter (e.g. volume). A constraint is any mathematical limitation (e.g., >, <, =) placed on a system parameter value.

A feasible system has parameter values that meet all imposed system constraints. A goal is a more stringent limitation or set of limitations that, when met, increases the perceived system value. An objective is a parameter constructed such that it describes a direction of increasing system value. In a fictional example, a state may require that cars sold within that state have a minimum mileage standard of 25mpg; this forms a manufacturer's feasibility constraint. A tax credit is given as incentive for cars meeting a 30-mpg standard; this defines a goal. The manufacturer knows that the higher a car's mileage is, the greater their sales will be; this defines an objective.

"Distance," as used to compare competing systems, was first developed in formulating the theories and arithmetic of "fuzzy logic." Distance measures the divergence of two fuzzy numbers, or the degree of membership of a fuzzy number in a fuzzy set [Kaufman, Gupta, (17)]. As used for system comparisons, distance becomes the degree of divergence of a system from some ideal. The system closest to the ideal is the preferred system [Zeleny, (33)].

Model Construction

To illustrate the component selection methodology, eight modifications were selected from 855 proposed modifications in the "Shuttle Evolution Data Base"[22]. For these eight, quantitative data have been tabulated for design, development, test, and evaluation (DDTE) cost, delta cost, weight delta, and Crit 1's (see Table 1). DDTE Cost is the total expenditure required to research, design, and implement a proposed modification for four Shuttles. Delta (Δ) Cost refers to the total change in annual Shuttle fleet operating costs the change would effect. Weight Δ can represent a change in Shuttle weight or performance; for example a 10-pound reduction in Shuttle weight equates to a 10-pound payload performance increase. Crit 1, or Criticality 1, items are Shuttle components whose failure will result in the loss of vehicle and crew. The "Crit 1" number is the total quantity of such items removed from or added to the Shuttle by that modification; removing Crit 1 items results in a safer vehicle.

Table 1: Alternative Component (Modification) Listing

Alternatives	DDTE Cost $	Δ Cost $	Weight Δ #'s	Crit1's
c_1	3100000	-1000	-200	-2
c_2	$1.00*10^8$	-100000	-2200	0
c_3	$2.60*10^8$	-400000	50	0
c_4	$6.50*10^7$	-500000	-288	-6
c_5	$4.93*10^7$	-2000000	200	-13
c_6	$2.25*10^8$	-3000000	-3500	-37
c_7	$1.00*10^7$	0	-8000	0
c_8	$1.25*10^8$	0	-500	-44

For this example, feasibility and goal constraints will later be placed on DDTE Cost, Δ Cost, Weight Δ, and Crit 1's. As such, each of the four data categories forms a system parameter as listed in Table 2. Each of these parameters corresponds to an axis in a four-dimension n-space.

Table 2: Parameter Definitions

x_1 = DDTE Cost
x_2 = Δ Cost, annual operations cost change
x_3 = Weight Δ
x_4 = Crit 1's, change in quantity of Crit 1 items

Given defined parameters, each alternative component type c_k is described by an ordered list, also designated c_k. These lists are similar to catalog descriptions that list product characteristics that would interest a customer. Each position $c_{k,i}$ in the list contains the corresponding parameter value for a component of that type. Table 3 lists these component definitions. Parameter values for components are considered fixed properties. Components are vectorally additive only within the definition of the system vectors defined later.

Corresponding to a warehouse, the set of available alternative components (inventory) is designated as

$$I = \{i_1c_1 \quad i_2c_2 \quad i_3c_3 \quad i_4c_4 \quad i_5c_5 \quad i_6c_6 \quad i_7c_7 \quad i_8c_8\}, \tag{1}$$

where i_k = the quantity of type "k" components in the inventory,
= {0, 1}, for this example.

For this example, a single component of each type is initially available,

$$I_0 = \{1(c_1) \quad 1(c_2) \quad 1(c_3) \quad 1(c_4) \quad 1(c_5) \quad 1(c_6) \quad 1(c_7) \quad 1(c_8)\}.$$

Generally, any i_k could contain any positive integer number of components.

Table 3: Component Definitions

$$\mathbf{c}_k = [x_1 \quad x_2 \quad x_3 \quad x_4] \tag{2}$$

$$C = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ c_4 \\ c_5 \\ c_6 \\ c_7 \\ c_8 \end{bmatrix} = \begin{bmatrix} 3100000 & -1000 & -200 & -2 \\ 1.00E8 & -100000 & -2200 & 0 \\ 2.60E8 & -400000 & 50 & 0 \\ 6.50E7 & -500000 & -288 & -6 \\ 4.93E7 & -2000000 & 200 & -13 \\ 2.25E8 & -3000000 & -3500 & -37 \\ 1.00E7 & 0 & -8000 & 0 \\ 1.25E8 & 0 & -500 & -44 \end{bmatrix}$$

Systems are defined as a set of components. An initial system S_0 (i.e. before starting the algorithm) may be empty or have baselined components that the algorithm may remove. The Shuttle has thousands of existing components. However, in this example these components are not removable and are not included in S. If a proposed modification could potentially replace an existing component, then that existing component would be included in the initial system set. For this example, the system set is represented by

$$S = \{s_1c_1 \quad s_2c_2 \quad s_3c_3 \quad s_4c_4 \quad s_5c_5 \quad s_6c_6 \quad s_7c_7 \quad s_8c_8\}, \qquad 3)$$

where $s_k = 1$ if c_k is included in the system,

$s_k = 0$ if c_k is not included in the system.

In the initial S_0, all s_k equal 0; the system set is empty.

To compare performances of competing alternative systems, each system is plotted in *4*-space based on its performance parameter values. A system vector is constructed to aggregate the effects of components included within a system. In this example, each system parameter is an additive function resulting in a system vector definition

$$\left[\sum_{k=1}^{8} s_k c_{k,1} \quad \sum_{k=1}^{8} s_k c_{k,2} \quad \sum_{k=1}^{8} s_k c_{k,3} \quad \sum_{k=1}^{8} s_k c_{k,4} \quad 1\right]^T = s \qquad 4)$$

where $c_{k,i}$ = the i-th property value for component type c_k.

For this example, constraints defining feasibility were selected for each of the four defined parameters and are listed in Table 4. These values were chosen only for their value in demonstrating the methodology. Together these constraints define a region of system feasibility in n-space bounded by orthogonal planes. This volume defining feasibility is designated **F**.

Table 4: Feasibility Constraints

$x_1 \le 3.00*10^8$	$x_2 \le 2.50*10^6$
$x_3 \le -8.00*10^3$	$x_4 \le -5.00*10^1$

A goal is also a set of bounded parameters defining a region in n-space and is designated **G**. To meet the goal defined for this example, the system must meet all conditions of feasibility at a lower DDTE cost as described in Table 5.

Table 5: Goal Definition

$x_1 \le 2.50*10^8$	$x_2 \le 2.50*10^6$
$x_3 \le -8.00*10^3$	$x_4 \le -5.00*10^1$

Method Illustration: Feasibility Search, Hill Climbing

The system construction algorithm starts with an inventory of possible components I_0 and an initial system S_0. First, components are removed from I_0 and added to S_0, constructing sequential systems whose corresponding vectors s gradually terminate closer to and finally within **F**. If adding components fails to result in a feasible system, components within S may be replaced with components from I. After a feasible system has been constructed, an attempt is made to modify it to meet the requirements of successive goals.

The first step in the system construction process is to establish an initial baseline system. Table 6 summarizes the system state prior to beginning the search algorithm. The initial baseline system S_0 contains no components, all $s_k = 0$. The baseline system vector s_0, coincides with the origin, each $s_i = 0$. The "$\mathbf{F}_i$" column lists the parameter values of the feasible volume **F**. The distance **d** and the shadow distance $\underline{\mathbf{d}}$ incorporate scaling factors, $_i$. The scaling factors are used to compensate for variations of parameter measurement. For example, "Crit 1's" are measured in the tens and "DDTE Cost" is measured in the tens of millions. These variations in scale do not affect system feasibility determination. However, they may affect algorithm performance. In this example, if scaling factors were not used, initial component selections would focus on reduction in DDTE cost because of its much higher value. Crit 1's would be ignored until DDTE Cost was very close to or within feasibility limits. Large-scale differences most often result in much larger numbers of algorithm iterations, and increase the chances of failing to reach feasibility.

Table 6: Initial System State, Iteration 0

$$S_0 = \{0(c_1)\ \ 0(c_2)\ \ 0(c_3)\ \ 0(c_4)\ \ 0(c_5)\ \ 0(c_6)\ \ 0(c_7)\ \ 0(c_8)\}$$

x_i	s_i	$\mathbf{F}_i$	$\mathbf{d}_i$	$\underline{\mathbf{d}}_i$
1 DDTE Cost	0	300M	0	300M
2 Δ Cost	0	-2.5M	2.5M	0
3 Weight Δ	0	-8000	8000	0
4 Crit 1's	0	-50	50	0

$\mathbf{d} = 1.732$

$\underline{\mathbf{d}} = 1.000$

$$\mathbf{d}_i = \begin{cases} s_i - \mathbf{F}_i \text{ if } s_i > \mathbf{F}_i \\ \mathbf{0} \text{ otherwise} \end{cases} \qquad \underline{\mathbf{d}}_i = \begin{cases} \mathbf{F}_i - s_i \text{ if } \mathbf{d}_i = \mathbf{0} \\ \mathbf{0} \text{ otherwise} \end{cases} \qquad 5)$$

$$\mathbf{d} = \sqrt{\sum_{i=1}^{4} (\ _i \mathbf{d}_i)^2} \qquad \underline{\mathbf{d}} = \sqrt{\sum_{i=1}^{4} (\ _i \underline{\mathbf{d}}_i)^2} \qquad _i = 1/\mathbf{F}_i \qquad 6)$$

Figure 1 depicts a three-dimensional n-space and includes axes for the system parameters that are not within the feasible limits: x_2, x_3, x_4. The point in **F** closest to s is [_,-1,-1,-1], normalized using the scaling factors $_2$ through $_4$. Since s_1 is the only system parameter within feasibility limits, $\mathbf{d} = 1$, normalized using $_1$.

In the first step of the algorithm, each alternative component c_k in I_0 is successively incorporated into the baseline system S_0 to form alternative systems, $S_{0(+k)} = (S_0 \cup c_k)$. Since the current system baseline $S_0 = \{\ \}$ (before iteration 1), in iteration 1 each alternative system $S_{0(+k)}$ consists of a single component c_k. For each $S_{0(+k)}$, a system vector $s_{0(+k)}$ is determined. Using these vectors, the distance $\mathbf{d}_{0(+k)}$, from $s_{0(+k)}$ to **F**, and the shadow distance $\underline{\mathbf{d}}_{0(+k)}$ are calculated, as listed in Table 7, for each $S_{0(+k)}$. Values associated with $(S_0 \cup c_6)$, the new root system, are listed below the tabulation for all systems.

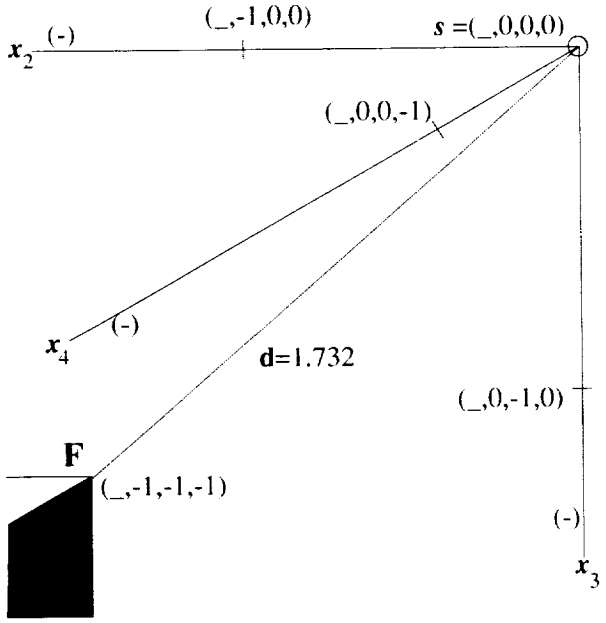

Figure 1: System Construction, Iteration 0

Table 7: System Construction, Iteration 1

7a: Results of Iteration

$S_{0(+k)}$	s_k	$\mathbf{d}_{0(+k)}$	$\mathbf{d}_0$-$\mathbf{d}_{0(+k)}$	$\underline{\mathbf{d}}_{0(+k)}$	$(\underline{\mathbf{d}}_{0(+k)})$-$\underline{\mathbf{d}}_0$	RATIO
$S_{0(+6)}$	**1**	**0.620**	**1.112**	**0.320**	**-0.680**	**0.432**
$S_{0(+5)}$	0	1.280	0.452	0.836	-0.164	0.288
$S_{0(+7)}$	0	1.414	0.318	0.967	-0.033	0.285
$S_{0(+1)}$	0	1.695	0.038	0.990	-0.010	0.027
$S_{0(+4)}$	0	1.531	0.201	0.783	-0.217	-0.016
$S_{0(+8)}$	0	1.376	0.356	0.583	-0.417	-0.061
$S_{0(+2)}$	0	1.564	0.168	0.667	-0.333	-0.166
$S_{0(+3)}$	0	1.649	0.083	0.133	-0.867	-0.783

Note: "(+k)" refers to the added component, e.g. $S_{0(+6)} \Rightarrow c_6$ has been added to the baseline system S_0.

RATIO = $(\mathbf{d}_0 - \mathbf{d}_{0(+k)}+)/(\underline{\mathbf{d}}_0 - \underline{\mathbf{d}}_{0(+k)})$, if $(\mathbf{d}_0 - \mathbf{d}_{0(+k)})>0$ and $(\underline{\mathbf{d}}_0 - \underline{\mathbf{d}}_{0(+k)}) \geq 1$ 7)

= $(\mathbf{d}_0 - \mathbf{d}_{0(+k)}+)+(\underline{\mathbf{d}}_0 - \underline{\mathbf{d}}_{0(+k)})$, if $(\mathbf{d}_0 - \mathbf{d}_{0(+k)})>0$ and $(\underline{\mathbf{d}}_0 - \underline{\mathbf{d}}_{0(+k)}) < 1$

= 0 otherwise

Note: The change in defining RATIO, when $(\underline{\mathbf{d}}_0 - \underline{\mathbf{d}}_{0(+k)}) < 1$, avoids distortingly high RATIO values because of very small denominators. In those rare cases when resource is gained ($\underline{\mathbf{d}}_{0(+k)} > \underline{\mathbf{d}}_0$), negative RATIO is avoided.

7b: Parameter Values for System ($S_0 \cup c_6$)

x_i	s_i	$\mathbf{F}_i$	$\mathbf{d}_i$	$\underline{\mathbf{d}}_i$
1 DDTE Cost	225M	300M	0	75M
2 Δ Cost	-3M	-2.5M	0	0.5M
3 Weight Δ	-3500	-8000	4500	0
4 Crit 1's	-37	-50	13	0

7c: Comparison of d and $\underline{\mathbf{d}}$ for baseline system and modified system

$S_0 \cup c_6$	S_0
$\mathbf{d} = 0.620$, $\underline{\mathbf{d}} = 0.320$	$\mathbf{d} = 1.732$, $\underline{\mathbf{d}} = 1.000$

Figure 2 shows the locations of the vectors resulting from alternative systems $S_{0(+1)}$ through $S_{0(+8)}$, the baseline system vector s_0, and the feasible volume **F**. The vector for $S_{0(+6)}$ terminated closest to **F**, and resulted in the highest RATIO. For the next iteration, $S_{0(+6)}$ becomes the new baseline system S_0.

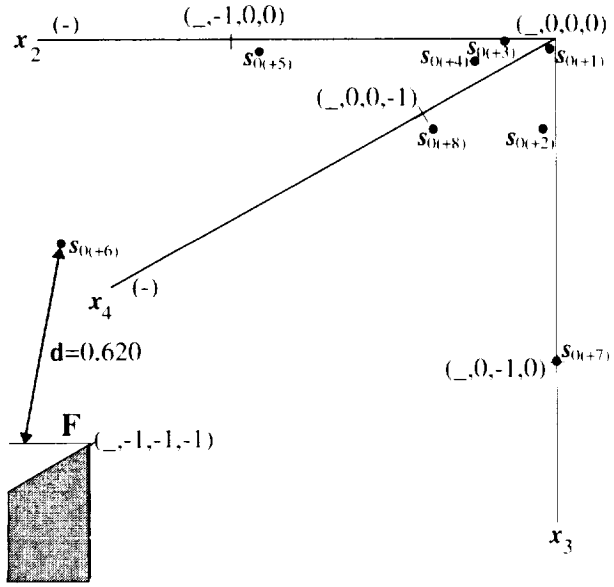

Figure 2: System Construction, Iteration 1

In iteration 2 (Table 8), the process of iteration 1 repeats. Alternative systems are formed combining c_6 successively with the remaining alternative components. In this iteration, the combination of c_6 and c_5 results in the largest RATIO of decrease in **d** to decrease in $\underline{\mathbf{d}}$.

Table 8: System Construction, Iteration 2

8a: Results of Iteration

$S_{0(+k)}$	s_k	$\mathbf{d}_{0(+k)}$	$\mathbf{d}_0$-$\mathbf{d}_{0(+k)}$	$\underline{\mathbf{d}}_{0(+k)}$	$(\underline{\mathbf{d}}_{0(+k)})$-$\underline{\mathbf{d}}_0$	RATIO
$\mathbf{S_{0(+6)}}$	**1**					
$\mathbf{S_{0(+5)}}$	**1**	**0.588**	**0.032**	**1.004**	**0.684**	**0.716**
$S_{0(+7)}$	0	0.260	0.360	0.528	0.207	0.567
$S_{0(+8)}$	0	0.527	0.093	0.651	0.331	0.424
$S_{0(+4)}$	0	0.545	0.075	0.401	0.081	0.156
$S_{0(+2)}$	0	0.396	0.223	0.240	-0.080	0.143
$S_{0(+1)}$	0	0.581	0.039	0.312	-0.008	-0.031
$S_{0(+3)}$	0	0.878	-0.259	0.360	0.040	0.000

8b: Parameter Values for System ($S_0 \cup c_5$)

x_i	s_i	$\mathbf{F}_i$	$\mathbf{d}_i$	$\underline{\mathbf{d}}_i$
1 DDTE Cost	274.3M	300M	0	25.7M
2 Δ Cost	-5M	-2.5M	0	2.5M
3 Weight Δ	-3300	-8000	4700	0
4 Crit 1's	-50	-50	0	0

8c: Comparison of d and $\underline{\mathbf{d}}$ for baseline system and modified system

$S_0 \cup c_5$	S_0
$\mathbf{d}$ = 0.588, $\underline{\mathbf{d}}$ = 1.004	$\mathbf{d}$ = 0.620, $\underline{\mathbf{d}}$ = 0.320

Figure 3 depicts the seven alternative system vectors and the baseline system vector. Since all parameters are algebraically additive, the alternative system vectors have been translated by simple vector addition to s_0. Notice that several vectors are closer to **F** than $s_{0(+5)}$. However $s_{0(+5)}$ had the highest RATIO of decrease in **d** to decrease in $\underline{\mathbf{d}}$.

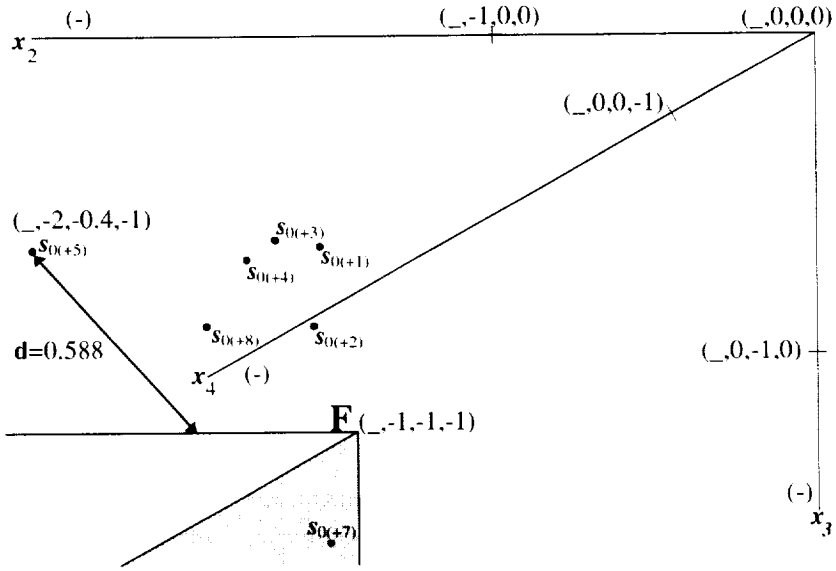

Figure 3: System Construction, Iteration 2

In the third iteration (Table 9), c_7 is the first to be considered for addition to the baseline system. The alternative system formed when c_7 is added meets all conditions for feasibility. At this point, goals are not a consideration and this stage of the algorithm ends. No other alternative components are evaluated. The feasible baseline system consists of $S_0 = \{c_6, c_5, c_7\}$. This set of components forms the baseline system for the start of the goal search.

Table 9: System Construction, Iteration 3

9a: Results of Iteration

$S_{0(+k)}$	s_k	$\mathbf{d}_{0(+k)}$	$\mathbf{d}_0$-$\mathbf{d}_{0(+k)}$	$\underline{\mathbf{d}}_{0(+k)}$	$(\underline{\mathbf{d}}_{0(+k)})$-$\underline{\mathbf{d}}_0$	RATIO
$S_{0(+6)}$	**1**					
$S_{0(+5)}$	**1**					
$S_{0(+7)}$	**1**	**0**	**0.588**	**0.528**	**-0.476**	**0.111**

9b: Parameter Values for System ($S_0 \cup c_7$)

x_i	s_i	$\mathbf{F}_i$	$\mathbf{d}_i$	$\underline{\mathbf{d}}_i$
1 DDTE Cost	284.3M	300M	0	15.7M
2 Δ Cost	-5M	-2.5M	0	2.5M
3 Weight Δ	-11300	-8000	0	33000
4 Crit 1's	-50	-50	0	0

9c: Comparison of d and $\underline{\mathbf{d}}$ for baseline system and modified system

$S_0 \cup c_7$	S_0
$\mathbf{d} = 0.000$, $\underline{\mathbf{d}} = 1.083$	$\mathbf{d} = 0.588$, $\underline{\mathbf{d}} = 1.004$

Method Illustration: Goal Search, Backtracking

Table 10 contains the starting conditions for the goal search portion of the algorithm. The budget for DDTE cost is reduced from \$300M to \$250M. All other conditions set for this goal are the same as those set for feasibility. In this initial goal search iteration, only the baseline system is evaluated in order to determine the new baseline **d** and $\underline{\mathbf{d}}$.

Table 10: System Modification, Iteration 4

$S_0 = \{0(c_1)\ \ 0(c_2)\ \ 0(c_3)\ \ 0(c_4)\ \ 1(c_5)\ \ 1(c_6)\ \ 1(c_7)\ \ 0(c_8)\}$

x_i	s_i	$\mathbf{G}_i$	$\mathbf{d}_i$	$\underline{\mathbf{d}}_i$
1 DDTE Cost	284.3M	300M	0	15.7M
2 Δ Cost	-5M	-2.5M	0	2.5M
3 Weight Δ	-11300	-8000	0	33000
4 Crit 1's	-50	-50	0	0

$\mathbf{d} = 0.114$, $\underline{\mathbf{d}} = 1.082$

In the fifth iteration (Table 11), the remaining components are sequentially added to S_0 and the distance to the goal **G** is determined for each. None of the alternative component incorporations resulted in a reduction of **d** as compared to the baseline system. This would be expected since the addition of components increases system DDTE Cost. The next iteration begins using a backtracking strategy in an attempt to find an alternative basis system that will eventually allow *s* to terminate closer to, or within, **G**.

In this backtracking strategy, successive components c_k are removed from S_0 to form alternative root systems $S_{0(-k)}$. Each of these alternative root systems is tested using the hill-climbing technique used to reach **F**. The alternative root, with any added components, that terminates closest to **G** (or **F** if appropriate) becomes the new basis system.

Table 11: System Modification, Iteration 5

$S_{0(+k)}$	s_k	$\mathbf{d}_{0(+k)}$	$\mathbf{d}_0-\mathbf{d}_{0(+k)}$	$\underline{\mathbf{d}}_{0(+k)}$	$(\underline{\mathbf{d}}_{0(+k)})-\underline{\mathbf{d}}_0$	RATIO
$\mathbf{S_{0(+6)}}$	**1**					
$\mathbf{S_{0(+5)}}$	**1**					
$\mathbf{S_{0(+7)}}$	**1**					
$S_{0(+8)}$	0	0.531	-0.417	1.414	0.332	0
$S_{0(+4)}$	0	0.331	-0.217	1.287	0.205	0
$S_{0(+2)}$	0	0.448	-0.333	1.247	0.165	0
$S_{0(+1)}$	0	0.125	-0.010	1.093	0.011	0
$S_{0(+3)}$	0	0.981	-0.867	1.229	0.147	0

Iteration six (Table 12) establishes an alternative root system $S_{0(-6)}$ by removing c_6 from the current S_0. That alternative system is then tested for goal achievement. In this case, **d** is greater than 0; the system does not meet goal conditions. Removal of c_6 has reduced DDTE Costs, but all other parameters moved away from the goal. The net effect is a distance increase.

Table 12: System Modification, Iteration 6

12a: System at Iteration 6

$$S = \{0(c_1)\ \ 0(c_2)\ \ 0(c_3)\ \ 0(c_4)\ \ 1(c_5)\ \ 0(c_6)\ \ 1(c_7)\ \ 0(c_8)\}$$

12b: Parameter Values for System ($S_0 \setminus c_6$)

x_i	s_i	$\mathbf{F}_i$	$\mathbf{d}_i$	$\underline{\mathbf{d}}_i$
1 DDTE Cost	59.3M	250M	0	190.7M
2 Δ Cost	-2M	-2.5M	.5M0	0
3 Weight Δ	-7800	-8000	2000	0
4 Crit 1's	-13	-50	370	0

12c: Comparison of d and $\underline{\mathbf{d}}$ for baseline system and modified system

$S_0 \setminus c_6$	S_0
$\mathbf{d} = 0.767$, $\underline{\mathbf{d}} = 0.636$	$\mathbf{d} = 0.114$, $\underline{\mathbf{d}} = 1.082$

The alternative root $S_{0(-6)}$ is expanded using the hill-climbing technique. Each of the previously unused components is successively added to $S_{0(-6)}$. The resulting systems are then evaluated. In Table 13, c_8 resulted in the largest RATIO and is added to $S_{0(-6)}$. This system provides a reduction in **d** as compared to $S_{0(-6)}$ and another iteration will be made.

Table 13: System Modification, Iteration 7

13a: Results of Iteration

$S_{0(+k)}$	s_k	$\mathbf{d}_{0(+k)}$	$\mathbf{d}_0$-$\mathbf{d}_{0(+k)}$	$\underline{\mathbf{d}}_{0(+k)}$	$(\underline{\mathbf{d}}_{0(+k)})$-$\underline{\mathbf{d}}_0$	RATIO
$S_{0(-6)}$	**0**					
$S_{0(+5)}$	**1**					
$S_{0(+7)}$	**1**					
$S_{0(+8)}$	**1**	**0.200**	**0.567**	**0.263**	**-0.373**	**0.194**
$S_{0(+1)}$	0	0.728	0.039	0.625	-0.010	0.029
$S_{0(+3)}$	0	0.777	-0.010	0.000	-0.636	0.000
$S_{0(+4)}$	0	0.620	0.147	0.419	-0.217	-0.070
$S_{0(+2)}$	0	0.757	0.010	0.392	-0.243	-0.234

13b: Parameter Values for System ($S_{0(-6)} \cup c_8$)

x_i	s_i	$\mathbf{F}_i$	$\mathbf{d}_i$	$\underline{\mathbf{d}}_i$
1 DDTE Cost	184.3M	250M	0	65.7M
2 Δ Cost	-2M	-2.5M	0.5M	0
3 Weight Δ	-8300	-8000	0	300
4 Crit 1's	-57	-50	0	7

13c: Comparison of d and $\underline{\mathbf{d}}$

$S_{0(-6)} \cup c_8$	$S_{0(-6)}$
$\mathbf{d} = 0.200$, $\underline{\mathbf{d}} = 0.263$	$\mathbf{d} = 0.767$, $\underline{\mathbf{d}} = 0.636$

In the next iteration (Table 14), the baseline alternative root system consists of components c_5, c_7, and c_8. Again the hill-climbing technique is employed and successive components are added to the alternative root. Upon the addition of c_4, all goal conditions are met and the algorithm ends having met a satisfying solution. The final baseline system, meeting all conditions of **F** and the **G**, is $S_0 = \{c_5, c_7, c_8, c_4\}$.

If this iteration had not been successful, hill climbing would have been repeated until no decrease in **d** was realized. These results would be stored for the alternative root $S_{0(-6)}$. The procedure would then be repeated for each of the remaining system components. If none of these alternative roots met the goal conditions, the alternative resulting in the greatest reduction in d would become the new baseline system. The process would then repeat. If no alternative root results in a reduction of d, the algorithm terminates.

Table 14: System Modification, Iteration 8

14a: Results of Iteration

$S_{0(+k)}$	s_k	$\mathbf{d}_{0(+k)}$	$\mathbf{d}_{(0)}$-$\mathbf{d}_{0(+k)}$	$\underline{\mathbf{d}}_{0(+k)}$	$(\underline{\mathbf{d}}_{0(+k)})$-$\underline{\mathbf{d}}_{(0)}$	RATIO
$S_{0(-6)}$	**0**					
$S_{0(+5)}$	**1**					
$S_{0(+7)}$	**1**					
$S_{0(+8)}$	**1**					
$S_{0(+1)}$	0	0.200	0.000	0.283	0.020	0.020
$S_{0(+3)}$	0	0.649	-0.449	0.143	-0.119	0.000
$S_{0(+4)}$	**1**	**0**	**0.200**	**0.419**	**0.157**	**0.357**
$S_{0(+2)}$						

14b: Parameter Values for System $(S_{0(-6)} \cup c_8 \cup c_4)$

x_i	s_i	$\mathbf{F}_i$	$\mathbf{d}_i$	$\underline{\mathbf{d}}_i$
1 DDTE Cost	249.3M	250M	0	0.7M
2 Δ Cost	-2.5M	-2.5M	0M	0
3 Weight Δ	-8588	-8000	0	588
4 Crit 1's	-63	-50	0	13

14c: Comparison of d and $\underline{\mathbf{d}}$

$S_{0(-6)} \cup c_8 \cup c_4$	$S_{0(-6)} \cup c_8$
$\mathbf{d} = 0$, $\underline{\mathbf{d}} = 0.270$	$\mathbf{d} = 0.200$, $\underline{\mathbf{d}} = 0.263$

Method Comparison With Previous Study Results

A variety of Shuttle evolution studies have been completed over the years. Of these, three used roughly the same database of possible modifications that the previous illustration was based on. The input and results of these three studies are used to validate results obtained using the method described in this paper.

The first study used a PC-based implementation of the analytic hierarchy process (AHP) decision analysis method [NASA, (21)]. Safety, Mission, Performance, Turnaround, and Cost were given relative weightings used to score Shuttle enhancement alternatives. These enhancements were then ranked and 25 were given a 1, 2, or 3 priority (Table 15).

To compare this first study's results with those using this paper's alternative method, the Weighted Total score, the Safety score and the Cost for all Priority 1 items were totaled. These results were then input as feasibility limits into the PC application of this paper's method. After 11 iterations, the minimum limits placed on Total and Safety were surpassed, while staying below the Cost limit. After the initial minimum conditions were met, the goal for Total was successively raised until it could not be met within the fund limit. This paper's method took 66 iterations and less than 1650 system calculations (<1 hour, 33MHZ 486). Exhaustive search would have required 33,554,432 system calculations. These results are compared in Table 16.

Table 15: Study One Results

	Priority One Items							Priority Three Items			
Alternative	**A**	**B**	**C**	**D**	**E**	F	G	**A**	**B**	**C**	**D**
Weighted Total	**482**	**478**	**475**	**433**	**419**	390	386	**99**	**96**	**95**	**91**
Safety	**500**	**500**	**500**		**500**		500	**100**	**100**	**100**	
Mission				**450**		450					
Payload	**-6**	**-20**			**-18**		-34				**-9**
Capability											
Turnaround											**100**
Life	**3**										
Cost	**-15**	**-2**	**-20**	**-17**	**-63**	-60	-80	**-1**	**-4**	**-5**	**-9**
Payback											**9**
Cost $M	**14.6**	**2.4**	**20**	**16.7**	**63**	59.9	80	**1.3**	**4.2**	**4.8**	**9.4**

	Priority Two Items													
Alternative	**A**	**B**	**C**	**D**	**E**	F	**G**	**H**	**I**	**J**	**K**	L	M	**N**
Weighted Total	**267**	**250**	**247**	**246**	**245**	240	**237**	**237**	**230**	**227**	**225**	211	192	**182**
Safety	**250**	**250**	**250**	**250**	**250**		**250**	**250**		**250**	**250**	250		**250**
Mission						450			**150**					
Payload	**-16**						**-2**					-39	210	
Capability	**20**						**30**						25	
Turnaround						-84	**-32**							**-63**
Life									**80**					
Cost	**-19**	**0**	**-3**	**-4**	**-5**	-126	**9**	**-13**	**-12**	**-23**	**-25**	-25	-18	**-5**
Payback	**4**								**12**					
Cost $M	**19**	**0.0**	**2.8**	**3.7**	**4.5**	126	**9.2**	**12.5**	**12**	**23.0**	**25**	24.7	18	**4.9**

Alternatives in boldface are those selected using the method outlined in this paper.

Table 16: Study One Results Comparison

	Study One	Alternative Approach
Total (points)	3500	5515
Safety (points)	2500	4800
Cost ($M)	257	253

Another internal NASA study using an alternative procedure ranked and scored 32 alternatives (Table 17) [ECON, (7)]. Scores or ratings were assigned for Nonrecurring Cost (NRC), Cost Savings, and Safety. These were combined into a total rank score. For the Safety category, each alternative was rated as having a high, medium, or low impact. For alternatives with similar utility scores, the alternative with a higher Safety rating was given preference.

To compare the second study results with those achievable by this paper's method, Nonrecurring Cost in $M (NRC), Savings ($M), and Safety were totaled for the top five ranked candidates. To quantify Safety, high was given a score of 3,000, medium 200, and low 1; these scores were

chosen to ensure that any alternative set of components would have at least as many high- and medium-rated components as the second study's top 5. These resulting sums were input for feasibility limits. After 5 iterations, Safety and Savings were exceeded at 2/3 the NRC. The limit for savings was increased in increments of 100 until no additional benefit could be achieved at the original NRC. The results are tabulated in Table 18.

This paper's method took 112 iterations and less than 3,584 system calculations. Exhaustive search would have required 4,294,967,296 system calculations.

Table 17: Study Two Results

Alter-native	NRC $M	$M Save	Safety	Comp. Score	Alter-native	NRC $M	$M Save	Safety	Comp. Score
1	**296**	**423**	**High**	**100**	**17**	**21**	**3**	**low**	**27**
2	334	122	Med.	96	18	90	43	low	26
3	300	-231	High	87	19	90	3	low	26
4	**135**	**62**	**High**	**81**	**20**	**79**	**38**	**low**	**23**
5	170	-15	low	57	21	68	3	low	20
6	**168**	**119**	**High**	**49**	**22**	**65**	**25**	**low**	**19**
7	**28**	**48**	**low**	**46**	**23**	**58**	**22**	**Med.**	**17**
8	155	-18	low	45	24	55	0	low	16
9	**87**	**119**	**High**	**42**	**25**	**39**	**0**	**low**	**11**
10	**143**	**63**	**Med.**	**42**	**26**	**25**	**-7**	**Med.**	**11**
11	141	0	Med.	41	27	33	13	low	9
12	33	-11	Med.	32	28	28	1	low	8
13	101	8	low	29	29	23	6	Med.	7
14	**23**	**3**	**low**	**28**	**30**	**19**	**-9048**	**low**	**6**
15	**40**	**162**	**Med.**	**28**	**31**	**4**	**6**	**low**	**1**
16	88	-18	low	27	32	3	6	low	1

Bold indicates final set of modifications selected by alternative method.

Table 18: Study Two Results Comparison

	Study Two	Alternative Approach
NRC, $M	1,235	1,217
Savings, $M	361	1,123
Safety	9,201	12,808
i.e.	3-highs	4-highs
	1-medium	4-mediums
	1-low	8 -lows

The third study was based on an exhaustive survey resulting in a list of 800 proposed Shuttle modifications [NASA, (22)]. The list included performance scores for DDTE costs, Recurring Costs, Safety, and Payload Capacity. Of the 800 alternatives, only 210 included DDTE costs and positive scores for at least one performance measurement.

The 20 highest scoring alternatives were aggregated to set the minimum standards for the test. The algorithm met Recurring Cost and Capacity scores, and exceeded the Safety and Total sums at half the DDTE cost. After meeting the minimum conditions, the goal values were raised by approximately a third with the same cost limit. These limits were also met (Table 19).

Table 19: Study Three Results Comparison

	Study Three	Alternative Approach
DDTE, ($M)	8,183	6,658
Safety (points)	94	182
Recurring Cost (points)	117	150
Capacity (points)	105	150
Total (points)	316	471

Running overnight on a 33MHZ 486, the algorithm took 83 iterations and less than 17,430 system calculations. Exhaustive search would have required $1.65*10^{63}$ system calculations.

Summary

The outlined methodology provides a robust means to catalog and model alternative components that are available for constructing a given system and to model that system. With these models, the methodology may be used to select components that together form a feasible system. Once a feasible system has been constructed, the methodology is capable of modifying that system to meet successive goals or to increase the value of an objective function.

In verification trials, the developed methodology was found capable of duplicating the results of an exhaustive search in far fewer iterations. When applied to the data used in three Shuttle evolution studies, the developed methodology produced component sets exceeding the performance of study recommendations at the same or a lower budget.

The only proven general method to produce optimality for component search problems is exhaustive search. Exhaustive search is usually impossible for large problems due to the number of possible component combinations. Although the described method is not an optimization method, it has proven useful in producing good and often close to optimal results. The described method provides a general and efficient means to evaluate and select from large numbers of alternative components in order to construct systems. Even at its current stage of development, it has proven to be a capable alternative to methods currently used for this type of problem.

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This paper describes a methodology to efficiently construct feasible systems, then modify feasible systems to meet successive goals by selecting from alternative components; a problem recognized to be n-p complete. The methodology provides a means to catalog and model alternative components. A presented system modeling structure is robust enough to model a wide variety of systems and provides a means to compare and evaluate alternative systems. These models act as input to a methodology for selecting alternative components to construct feasible systems and modify feasible systems to meet design goals and objectives. The presented algorithm's ability to find a restricted solution, as defined by a unique set of requirements, is demonstrated against an exhaustive search of a sample of proposed Shuttle modifications. The utility of the algorithm is demonstrated by comparing results from the algorithm with results from three NASA Shuttle evolution studies using their value systems and assumptions.

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